Phase Measurement System for Inter-Spacecraft Laser Metrology

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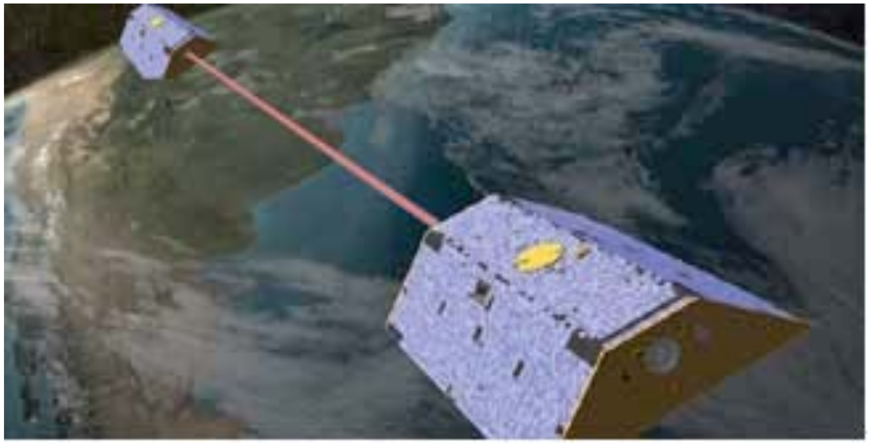
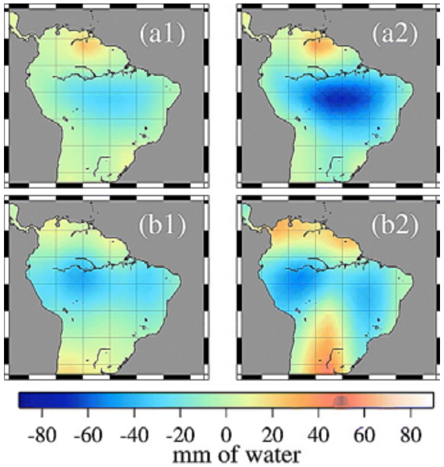
- The phase measurement system is being developed in parallel with a separate optical system development at U. Colorado/Ball Aerospace
  - See paper by M. Stephens, session A8P3

GRACE Mission



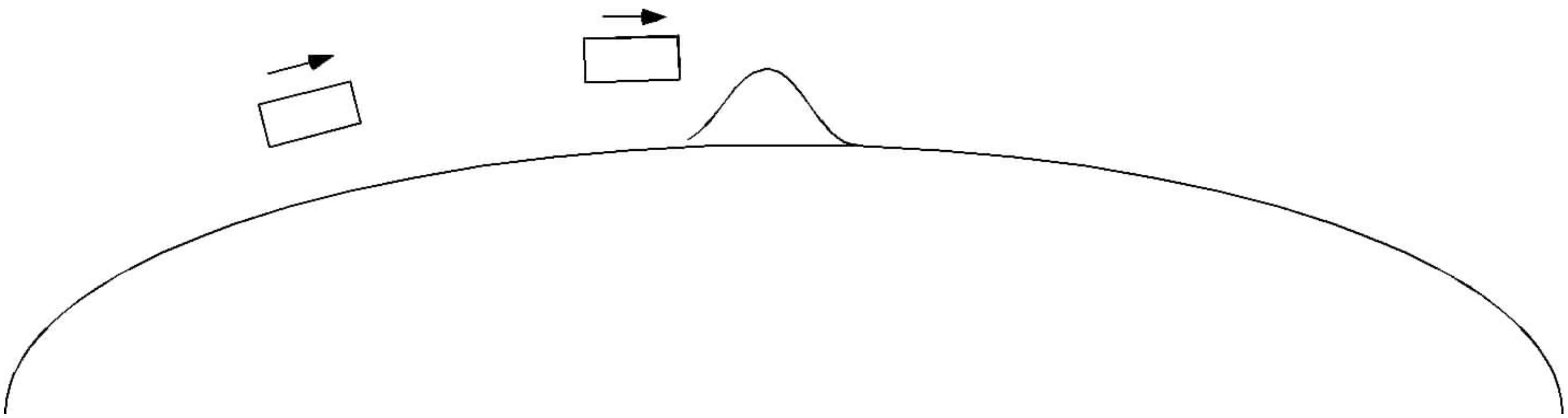


[Rowlands et al., 2005]

- Change in distance between spacecraft in low Earth orbit monitored to estimate underlying mass distribution
- Measurement accuracy (~ 100 nm) limited by
  - (1) thermal noise
  - (2) clock-like noise
    - includes frequency (in)stability of microwave signal source
- Gravity field accuracy also limited by
  - (3) non-gravitational forces on spacecraft
    - measured by accelerometer

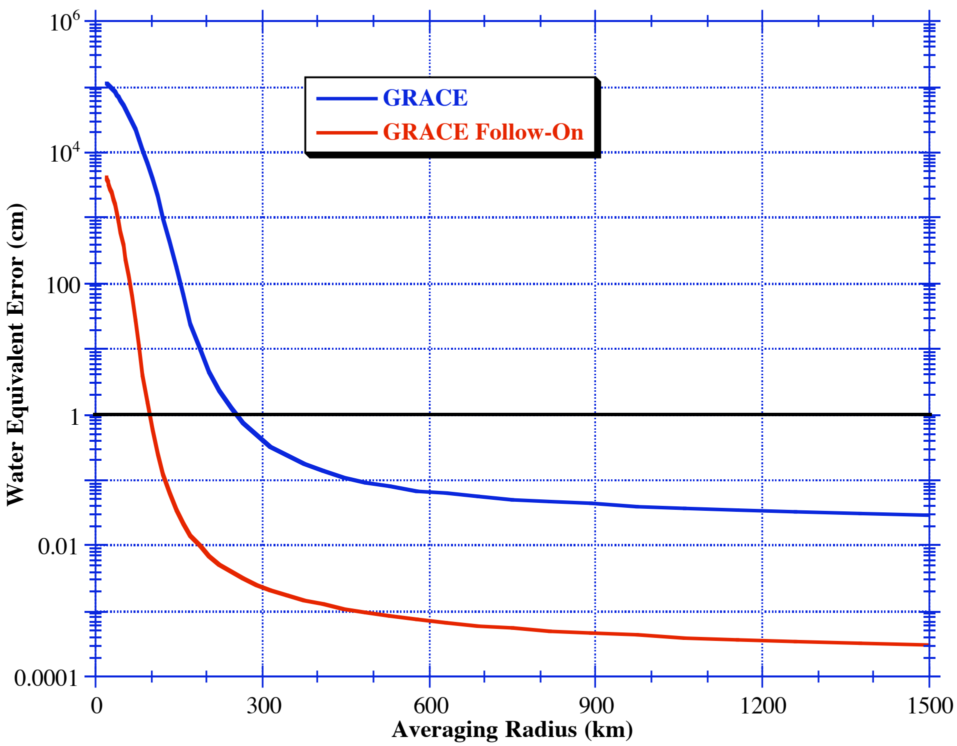
Range Change From Gravity

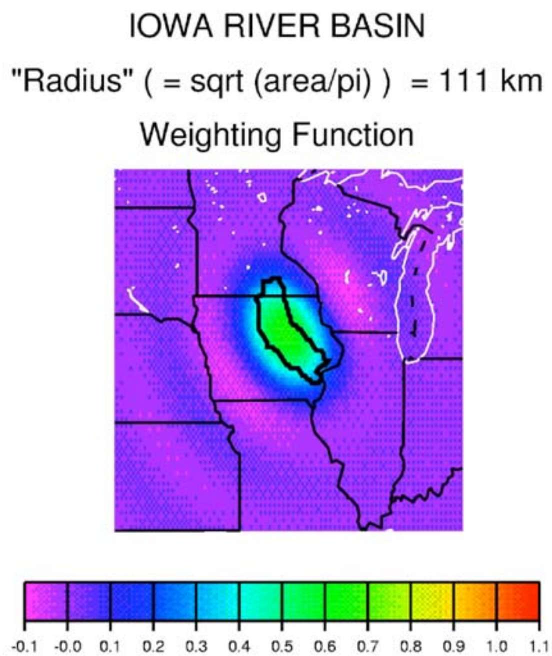
- Earth gravity features affect lead/trailing spacecraft at different times
  - Lead spacecraft encounters feature first
    - e.g. lead spacecraft speeds up towards mountain
      - Range to trailing spacecraft increases
  - Any unknown non-gravity forces acting on spacecraft also affect range
    - Calibrated out using accelerometer or drag-free sensor system



Goals for Next Gravity Mission

- Goal is to measure gravity changes with more precision over much smaller spatial scales
- Aim for x1000 improvement over GRACE in measurement system accuracy

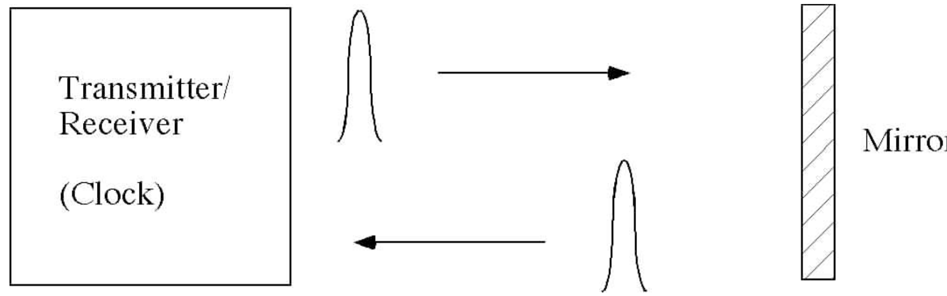


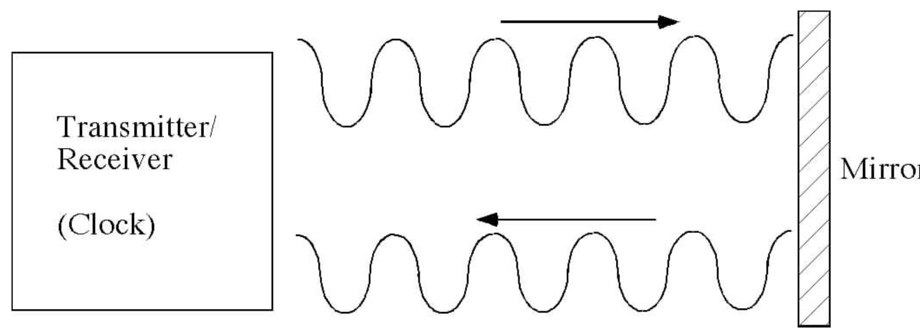


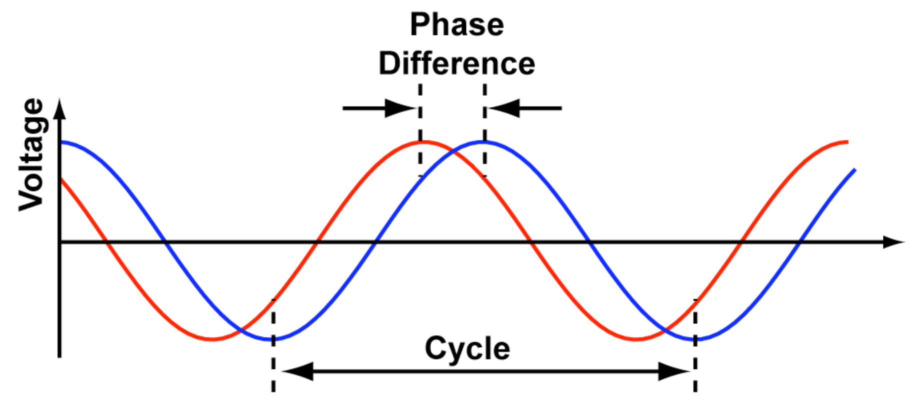
John Wahr

Ranging Measurement

- Range is inferred from measurement of round-trip light time
  - Pulsed is preferred when Transmitter/Receiver is on ground
    - High power concentration to overcome $1/r^4$ loss
  - Continuous preferred when 'mirror' is active
    - Better SNR; only $1/r^2$ losses
    - Higher precision from higher intrinsic frequency

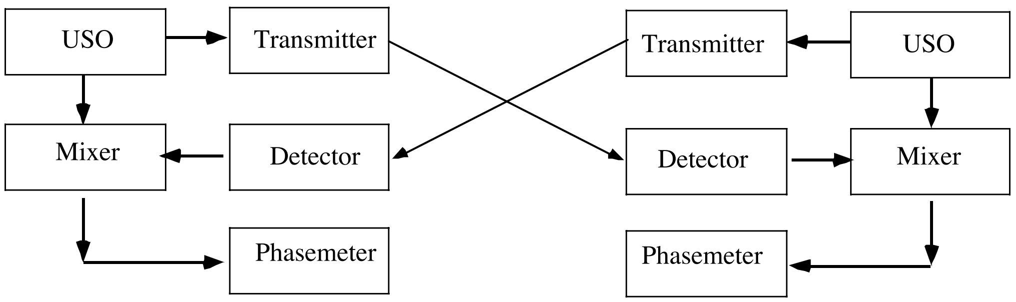


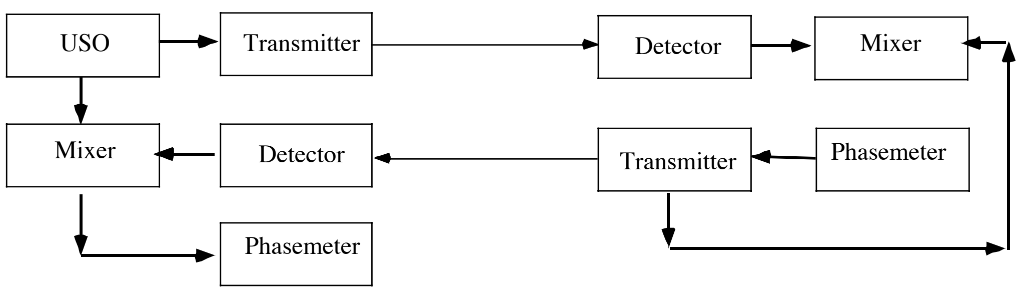




Dual One-Way versus Transceiver

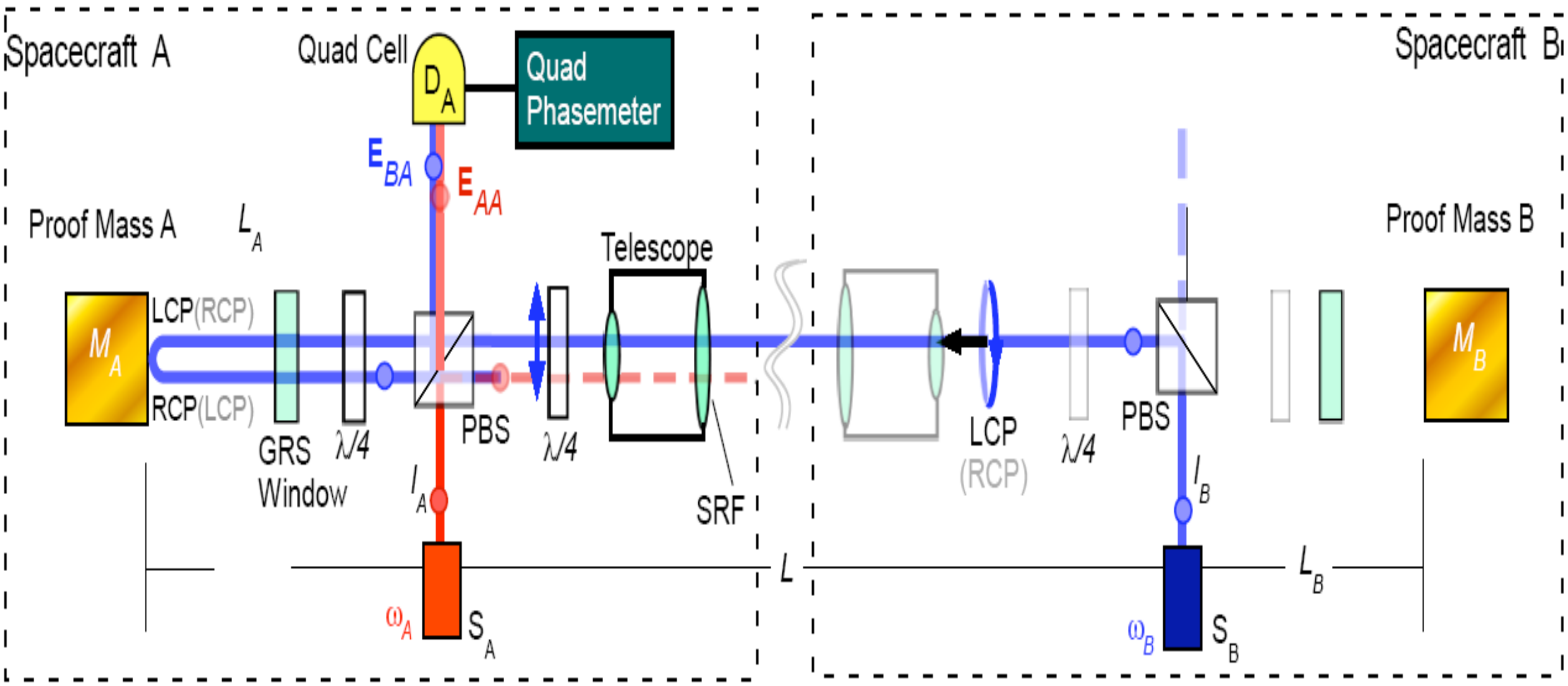
- GRACE uses independent transmission/detection at each spacecraft
  - Combination of data on ground determines range
- Laser metrology uses detection/locking-/transmission at one spacecraft
  - Otherwise laser frequencies would be too far apart
  - Fast phase meter needed for locking function





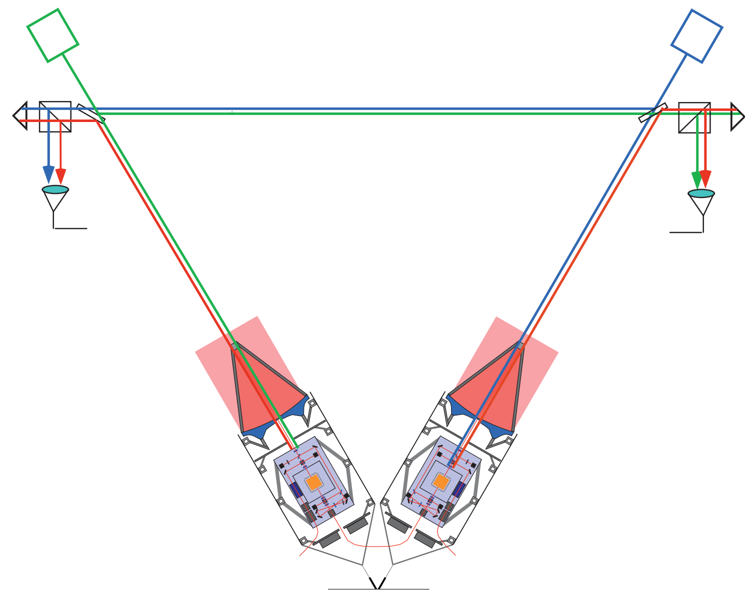
Interferometric Ranging Transceiver

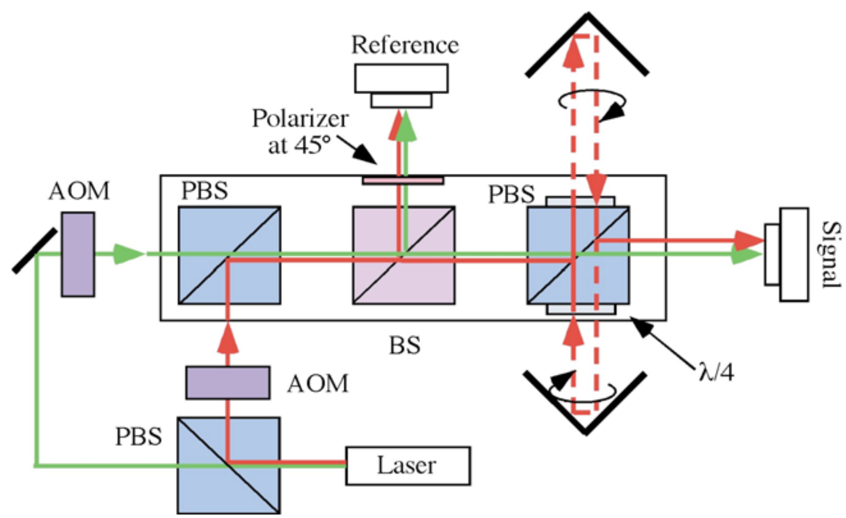
- Prototype optical benches being developed to transmit laser signals between spacecraft to measure range to <1 nm.
  - See paper by M. Stephens et al., this conference
- Range between freely-floating masses in drag-free spacecraft
  - See New Millennium Program ST7 paper



Other Applications

- LISA is based on a triangular interferometer, each arm similar to the IRT for GRACE-follow-on
  - LISA requires higher measurement accuracy, higher fringe frequency, lower frequency-rate
- SIM uses modulation interferometer to measures distance between reference corner cubes
  - More sensitive to cyclic errors
  - Can use lower signal frequency



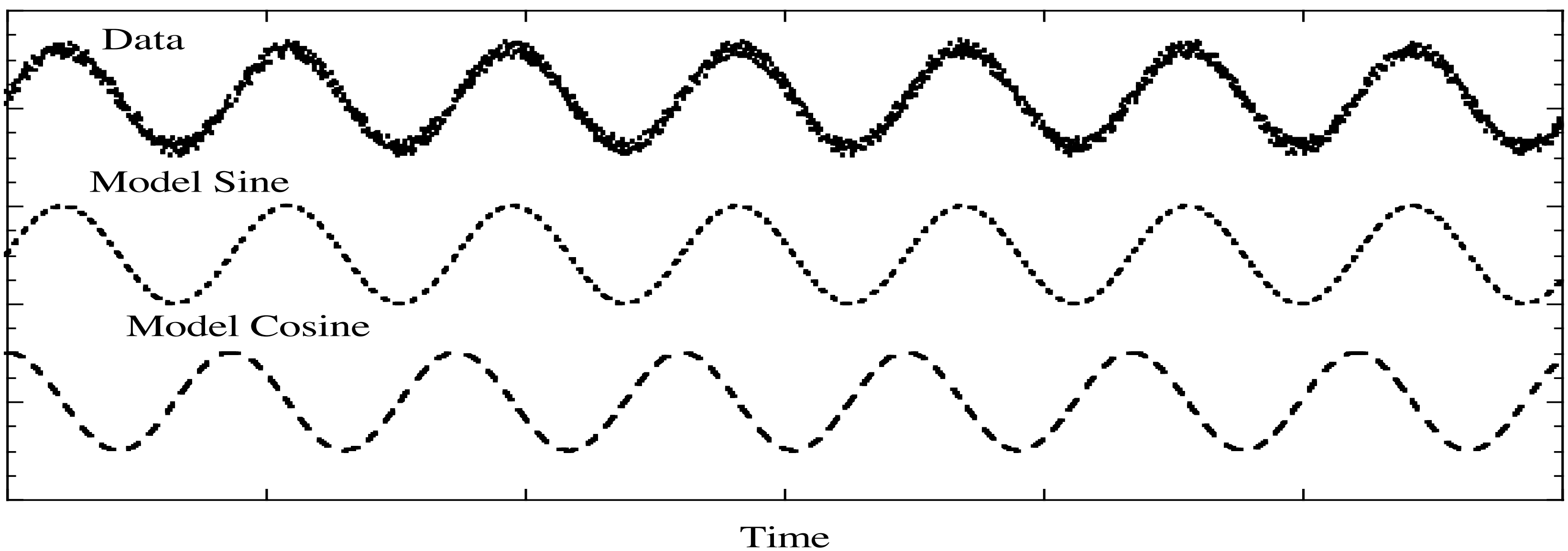


Laser Measurement Requirements

- Why new phasemeter development?
  - Laser signals have much higher carrier frequency
    - So Doppler shifts cause much higher signal frequency shifts and frequency rates
  - Lasers have much higher frequency variation
      - Compared with microwave signal locked to USO
    - Phasemeter must track with higher loop bandwidths
  - Higher accuracy requires better use of signal-to-noise ratio
    - Sampling must be 4-bit or greater
      - (GRACE uses 1-bit samples)
  - Lasers need to lock to other laser signals
    - Phasemeter output needed at >10kHz
    - Phasemeter should autonomously search for reference signal and lock
- Phasemeter must be insensitive to laser power fluctuations

Phase Measurement

- Local-model correlation method for phase measurement
  - Input signal (voltage) is multiplied (at each time)by;
    - Model of expected signal
    - Model of expected signal shifted by 90°
  - Cross-multiplications summed over integration time to get I, Q
  - Phase measurement is given by $\mathrm{Tan}^{-1}(I/Q)$

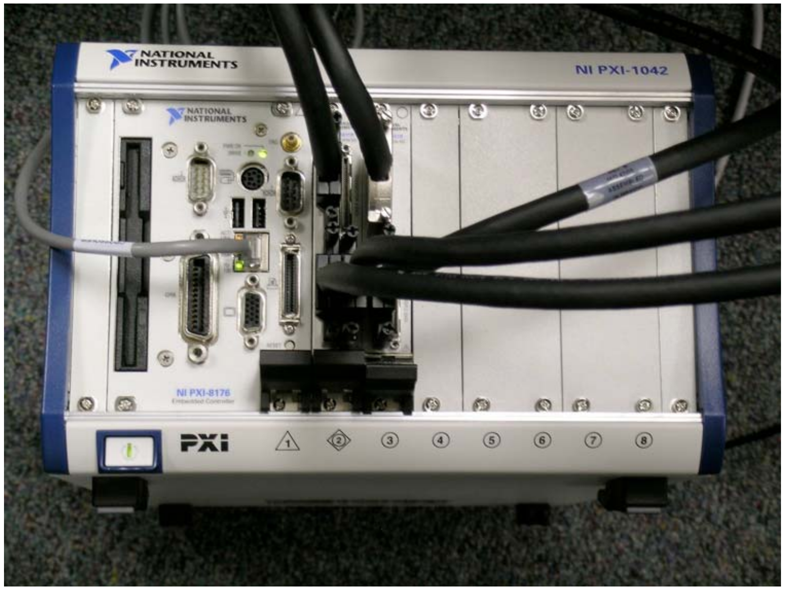


Breadboard Phasemeter Development

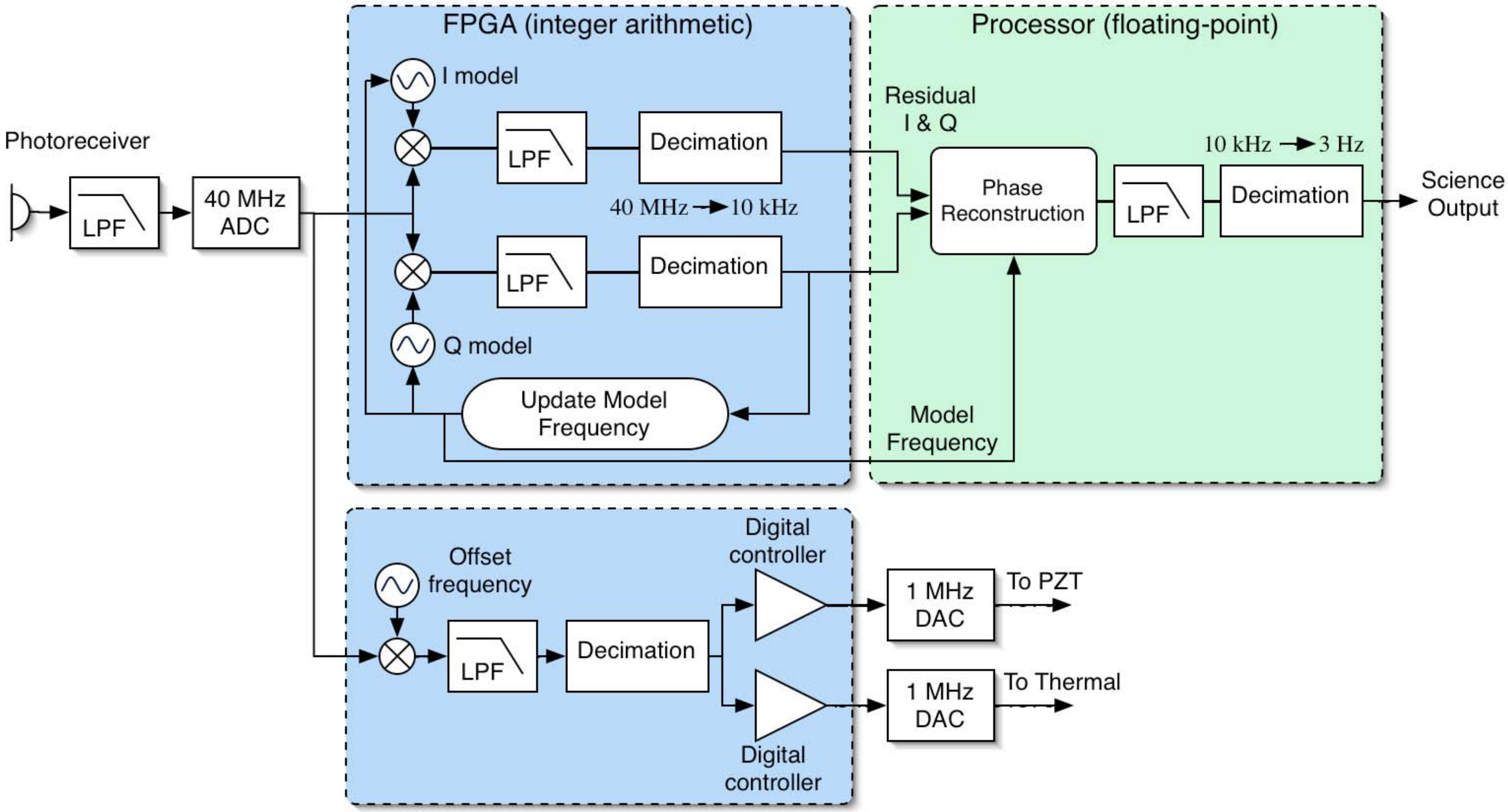
- Commercially available cards used for rapid development
- Labview-programmable FPGA card identified for ease of testing different algorithm implementations
- Fast analog-to-digital conversion cards available allow working over full expected range of Doppler variations
- A/D and FPGA run at 40 MHz
- Output available at 20 kHz for locking laser in ‘slave’ spacecraft
- Slower rate output used for highest precision
- Provides real time display and data logging

Breadboard Phasemeter Hardware

- Commercial rack-mount analog-to-digital converter
- PCXI cpu running real-time labview
  - Labview-programmable FPGA card
  - Upgraded in last 6 months to accommodate up to 4 channels
- Host PC tower for monitor and data logging (not shown)



Breadboard Phasemeter Architecture

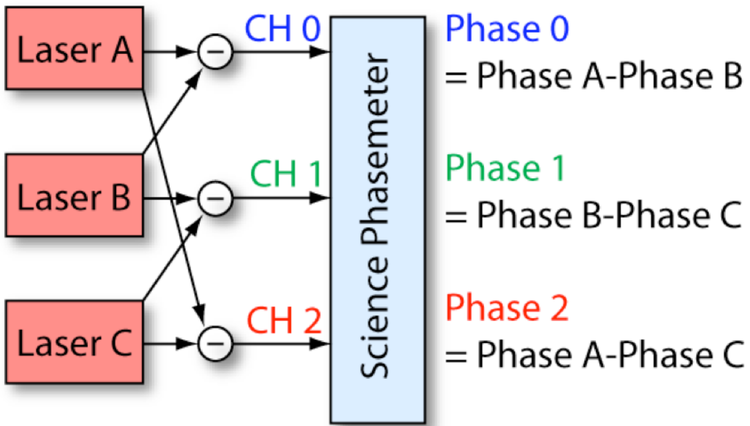


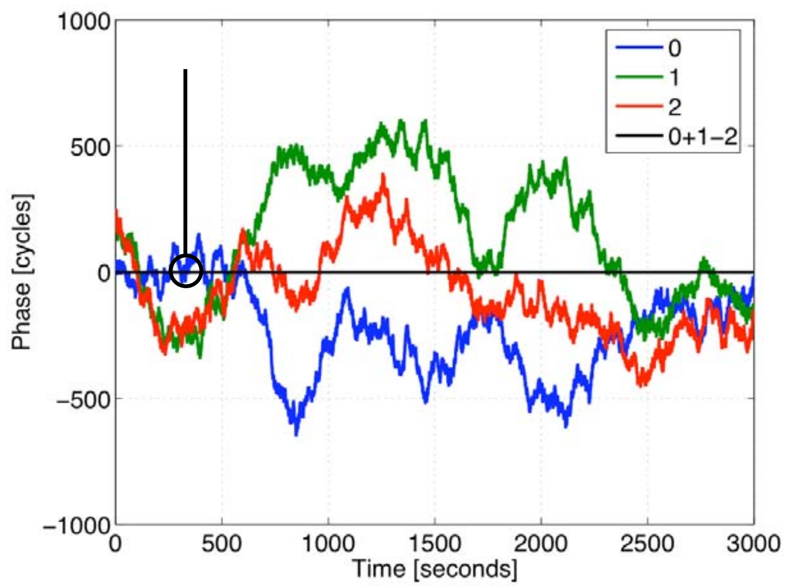
Accuracy & Dynamic Range

- Digitally tested dynamic range requirement.
  - Digitally generated 3 independent, laser-like noise sources such that,

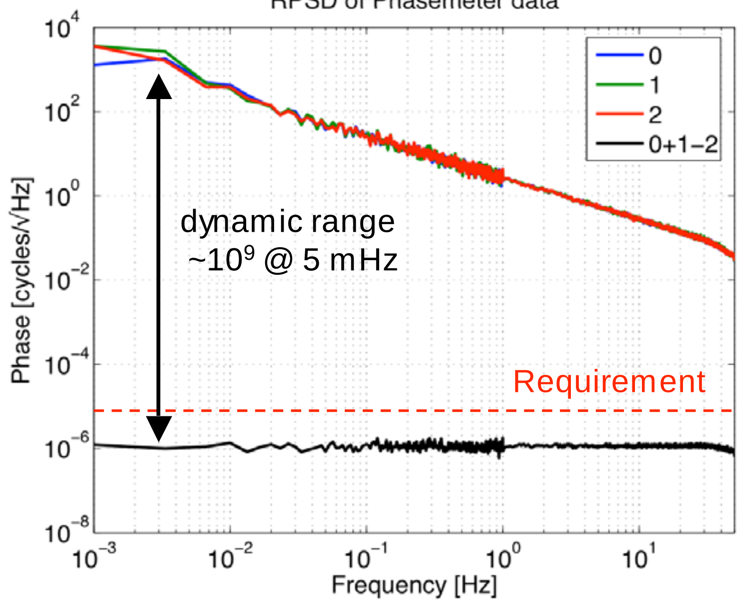
  Phase 0 + Phase 1 - Phase 2 = 0

Equivalent Optical Setup



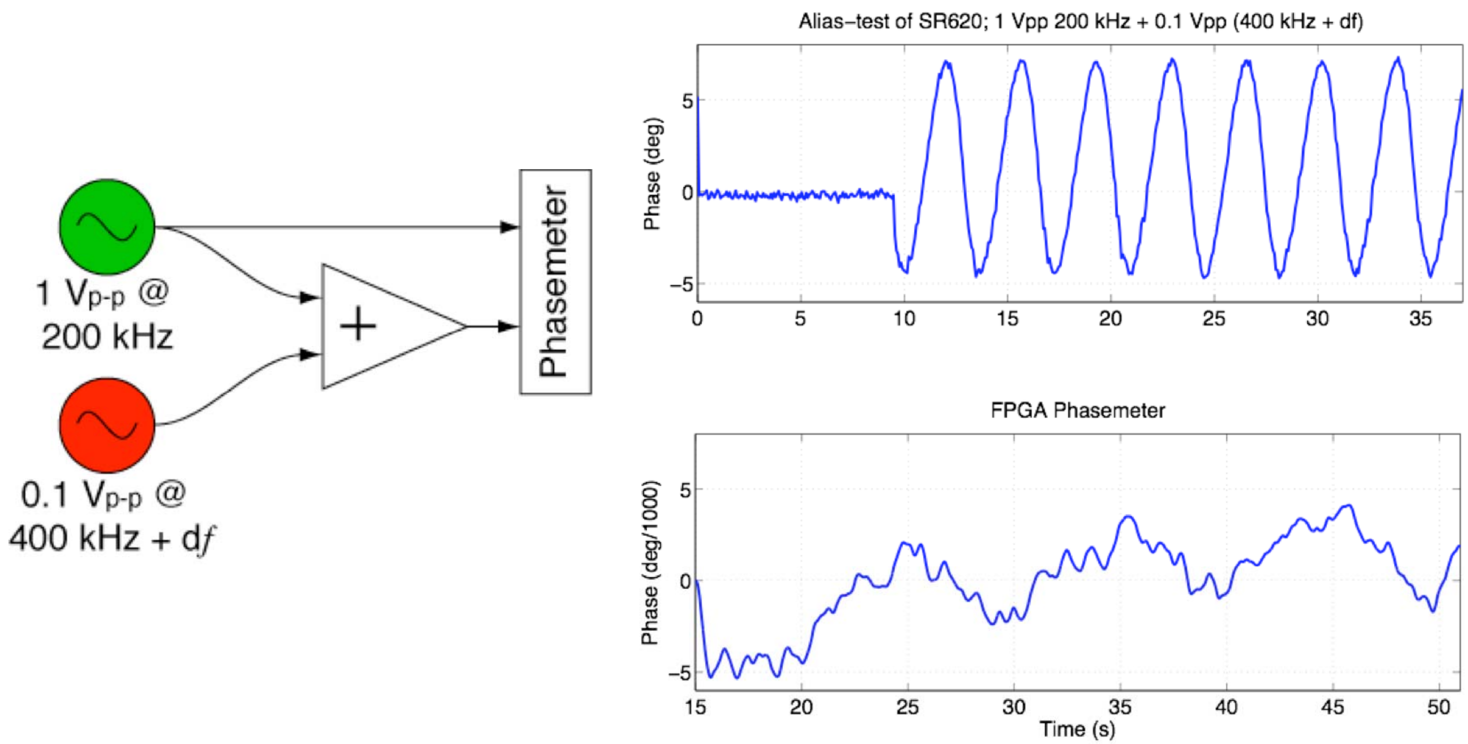


RPSD of Phasemeter data



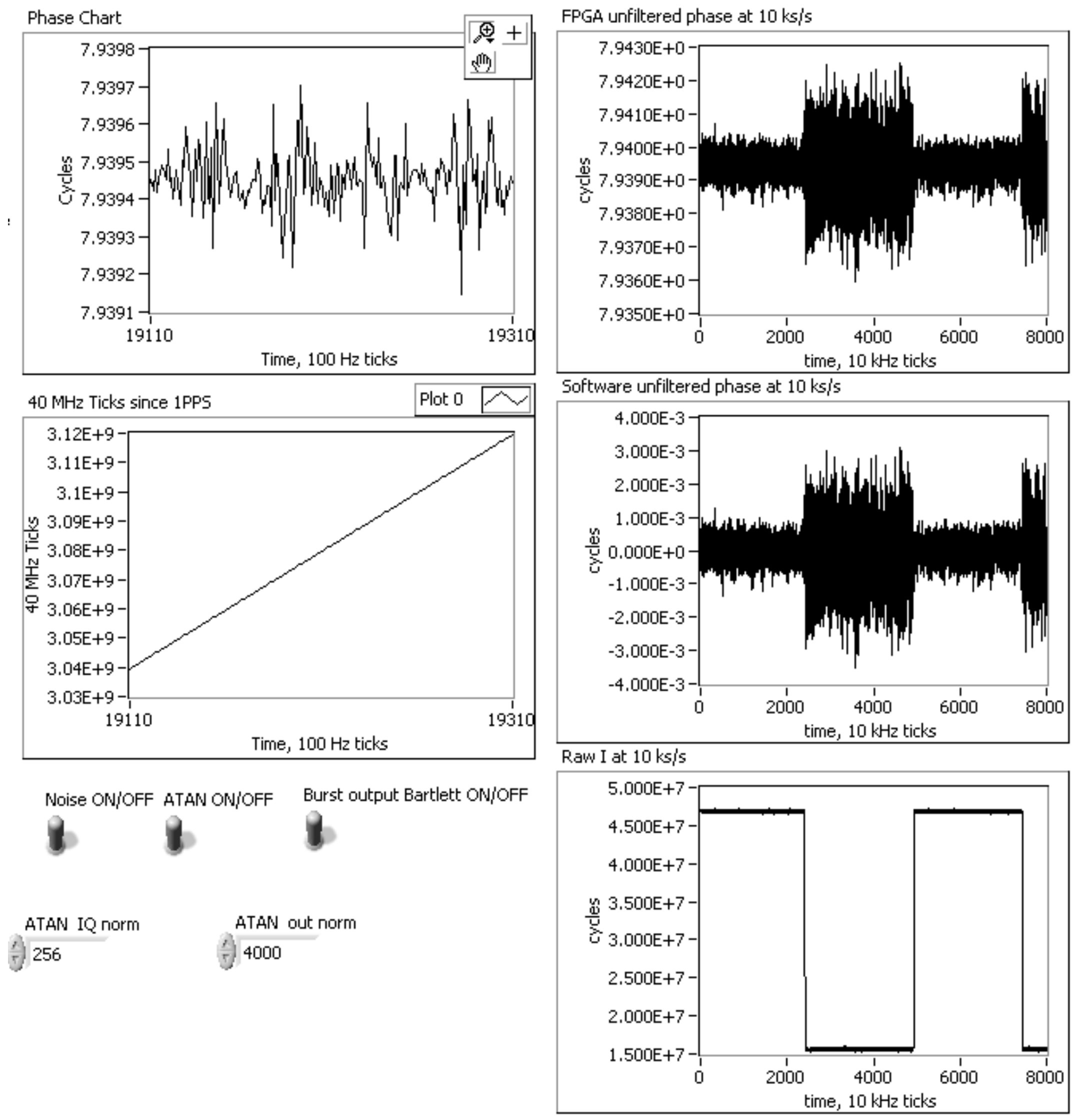
Anti-Aliasing

- Phasemeter designed to have aliasing suppression of 10^7 in the signal band.



Amplitude Sensitivity

- Phase measurement should be insensitive to amplitude changes
- Technique for adding random noise to most significant bit developed to limit sensitivity to amplitude changes
  - Also allows operation at signal frequencies which are integer-ratios of sampling frequency
  - At cost of slight, acceptable increase in noise



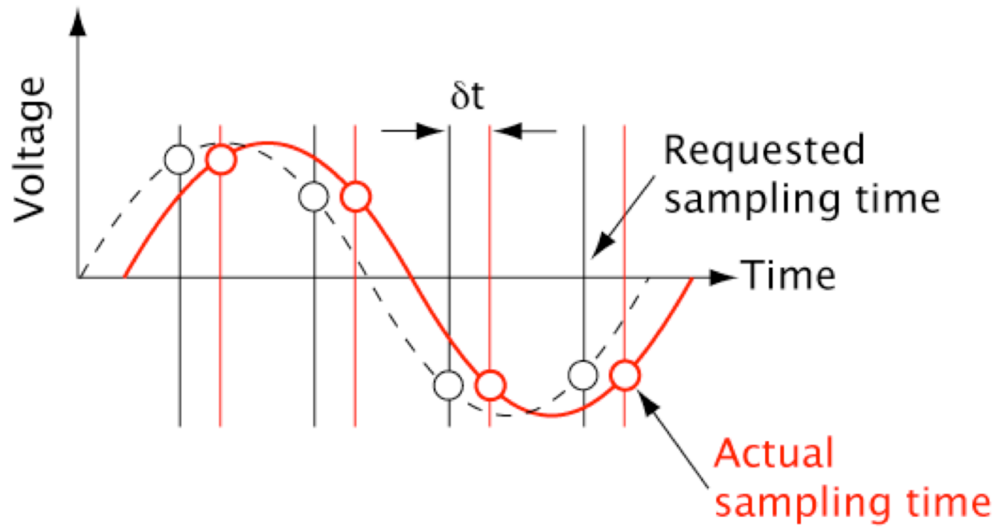
Sampling Jitter

- Jitter in the sampling time δt produces a phase error

$$\phi = \delta t \times f_{het}$$

- For 1 μcycle/$\sqrt{\text{Hz}}$ phase noise requirement, and a 20 MHz heterodyne frequency.

$$\delta t < 0.5 \times 10^{-13}\ \text{s}/\sqrt{\text{Hz}}$$

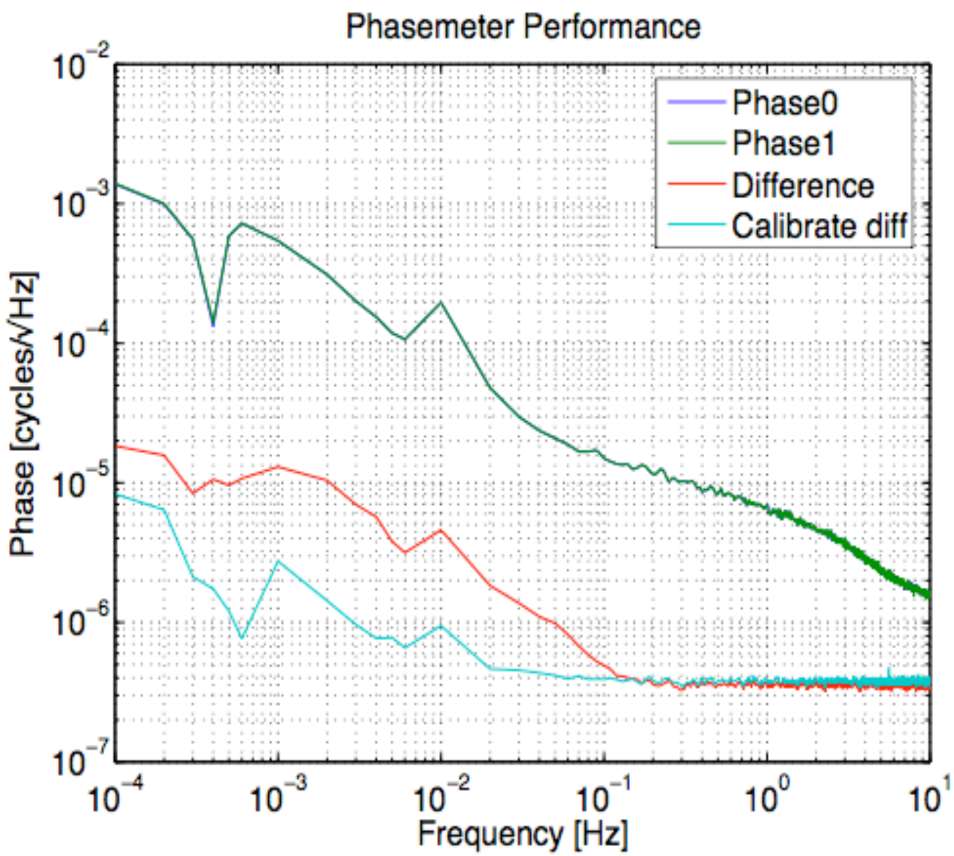


- Jitter in the sampling time arising from clock is already removed.
- Remaining sampling jitter is the fluctuating latency of the ADC.

Calibrate jitter by processing the phase of a known signal at a different frequency using the same ADC.

Sampling Jitter Calibration

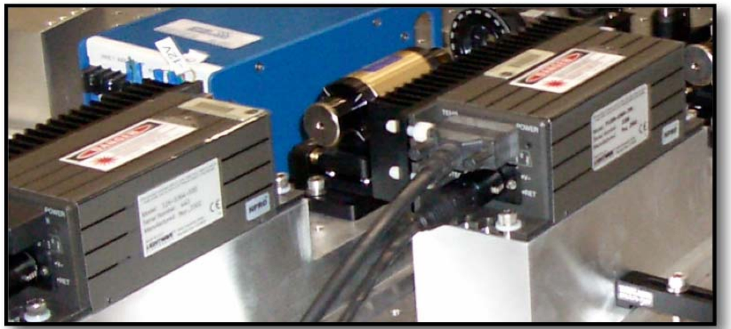
- A/D sampling jitter can be calibrated by adding signal locked to phasemeter reference clock to input of sampler
- Technique has been tested to show suppression of jitter noise to 10^{-6} cycle/sqrt(Hz)



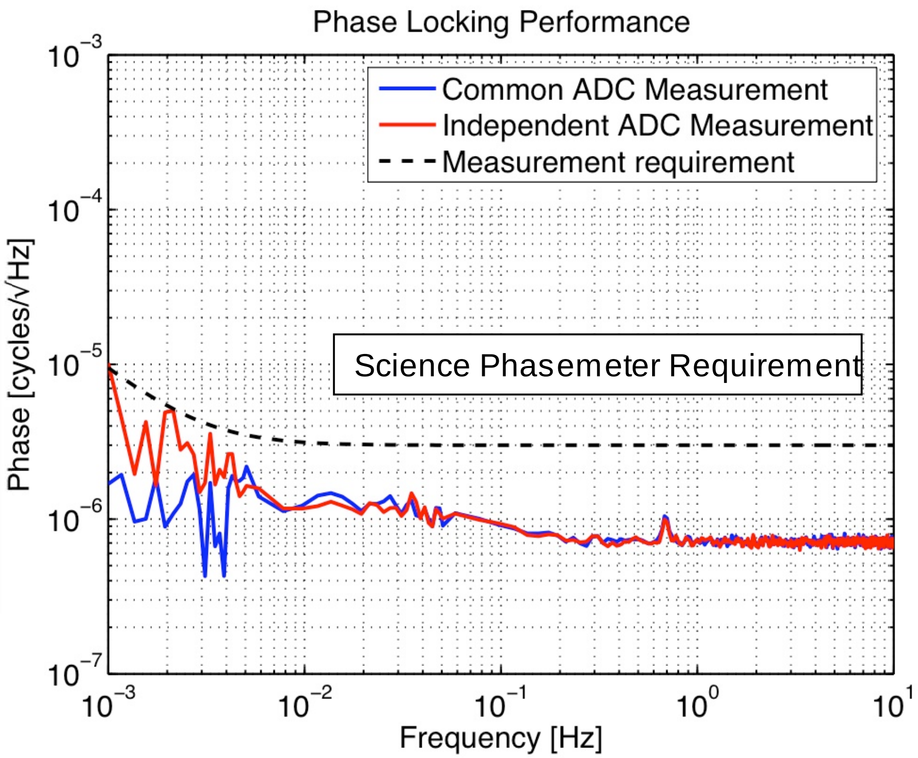
Laser Locking Test

The fast-phasemeter has been used to phase-lock two commercial NPRO lasers Maintains phase-lock indefinitely (weeks).

Used science phasemeter to evaluate locking performance.



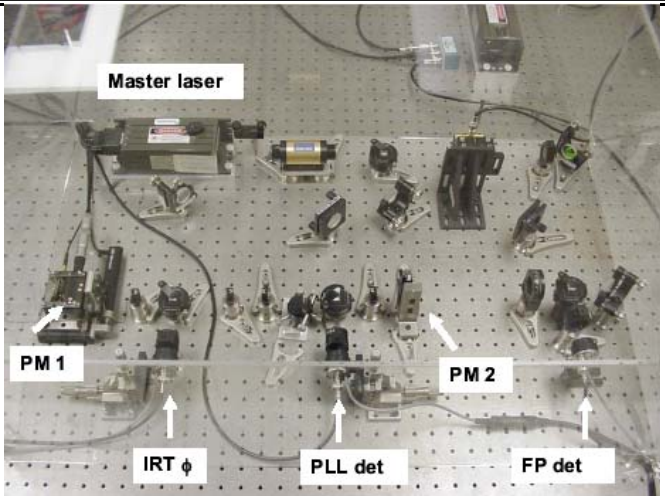
Two lasers locked using fast phasemeter

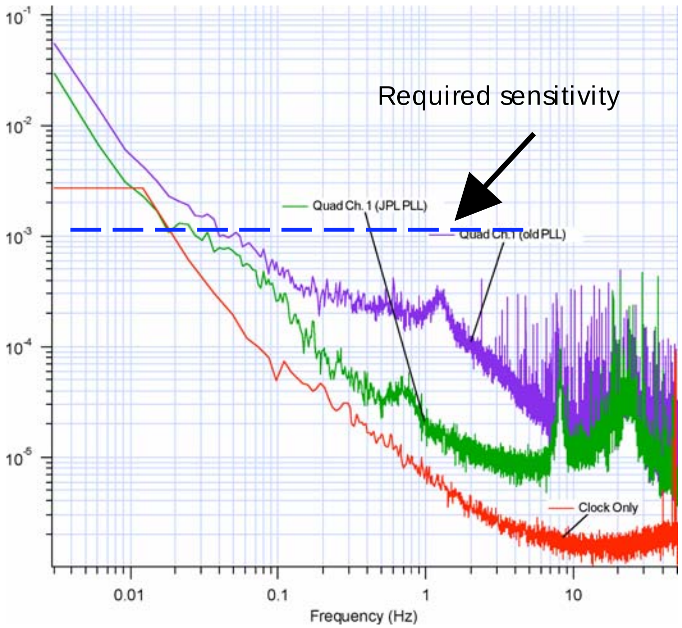


- Locked to < 1 μcycle/sqrt(Hz) above 100 mHz
- Locked to < 10 μcycle /sqrt(Hz) at 1 mHz
- Low frequency performance limited by ADC jitter.

Phasemeter in IRT Test Bed

- The PC phasemeter has been installed and tested in the IRT breadboard test bed at Ball Aerospace
- PC phasemeter works well with real optical signals
- The PC phasemeter has better performance than GRACE electronics previously used
  - Has much more flexible interface
  - Can be rapidly modifed if necessary
    - E.g. a ramp function to simulate orbit dynamics was implemented with a simple software update

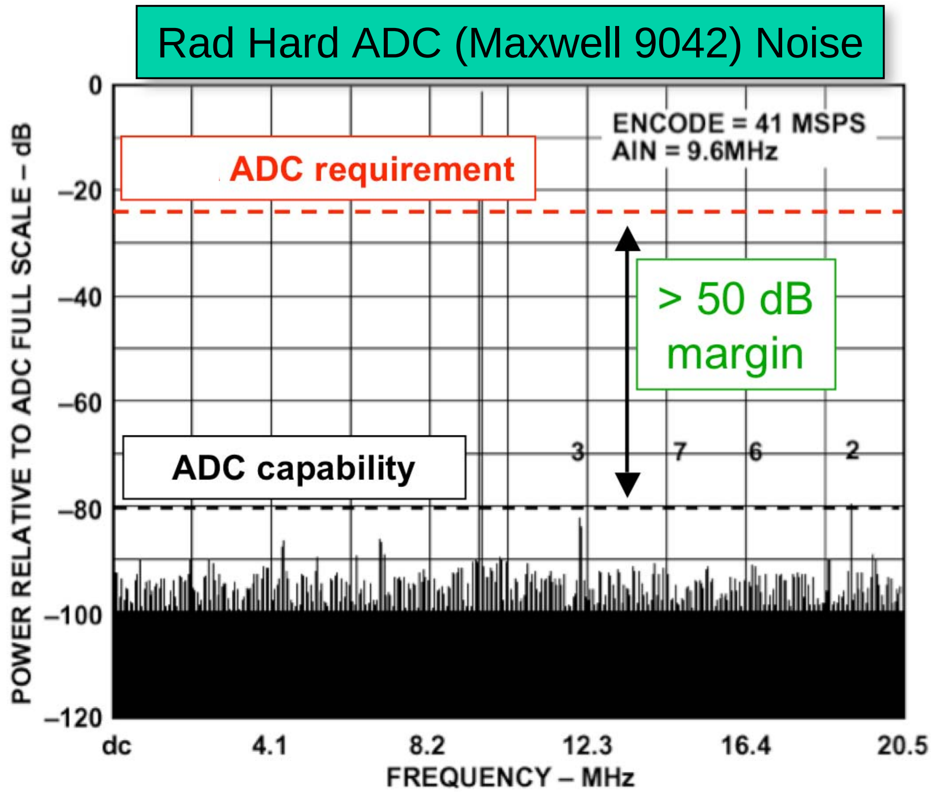




Figures from U. Colorado/BATC ITR Interim Review June 2006

Phasemeter Path to Flight

- Algorithms fully tested over required dynamic ranges
- Algorithms being ported to all integer arithmetic on FPGA
  - Compatible with flight FPGA components
- Suitable radiation hardened ADCs identified
  - e.g. Maxwell 9042:15 bit, 41 MS/s.



Summary

- Breadboard phasemeter works very well
  - Phasemeter has passed all digital and electronic tests
  - Critical requirements have been demonstrated
  - Tests of the phasemeter in a optical/electronic system are underway
- Phasemeter has a clear path to flight
  - All components are off the shelf items
  - Can be used for many applications